

Singlet-triplet qubits in Si quantum dots



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 - Xuedong Hu
 - Lukasz Cywinski
 - Qiuzi Li

Outline

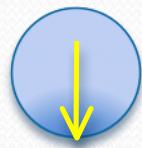
- Quantum computing schemes
- Singlet-triplet qubits
 - Initialization, manipulation, readout in double quantum dots
- Singlet-triplet qubits in Si quantum dots
 - Valleys determine orbital and spin spectrum
 - Initialization and manipulation
 - What do we need in order to have a qubit?
- Charge fluctuations
- Interface roughness
- Conclusions

Singlet-triplet qubits

- Two-spin states
 - Singlet and triplet
 - Energy difference ~ exchange coupling
- They form a two-level system
- Use this system as a qubit
 - Double quantum dot = 1 qubit
 - T_{\pm} moved away by Zeeman field
 - Left with S and T_0



S



T_+

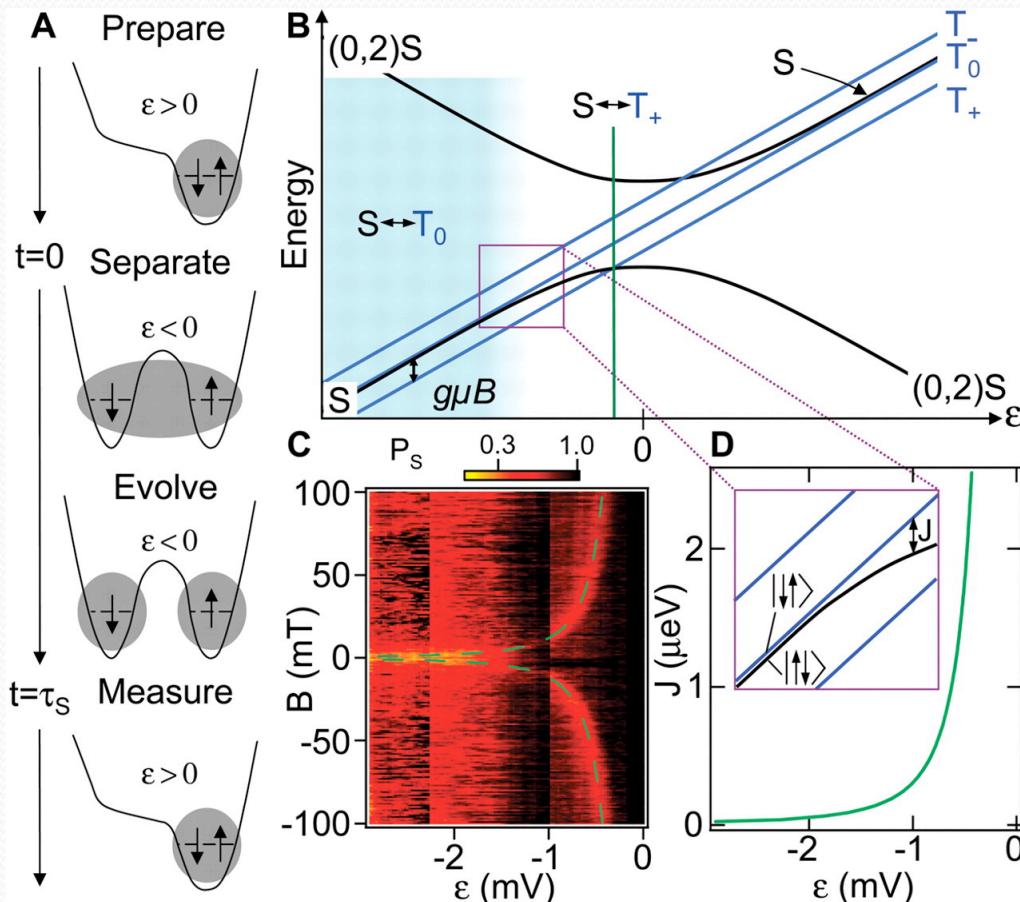


T_0



T_-

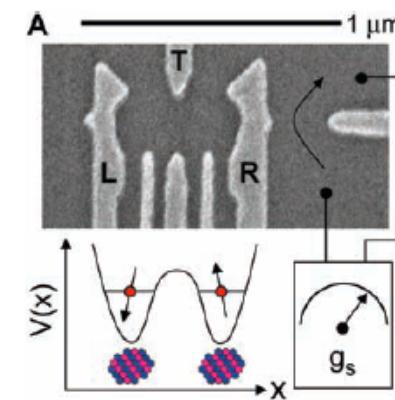
Singlet-triplet qubit



- Initialize $(0,2)$ singlet
 - $(0,2)$ triplet far away
- Control detuning
 - $(0,2)$ singlet and $(1,1)$ singlet close in energy
- Inhomogeneous B
 - Rotation between S , T
- Spin blockade
 - Probability of return

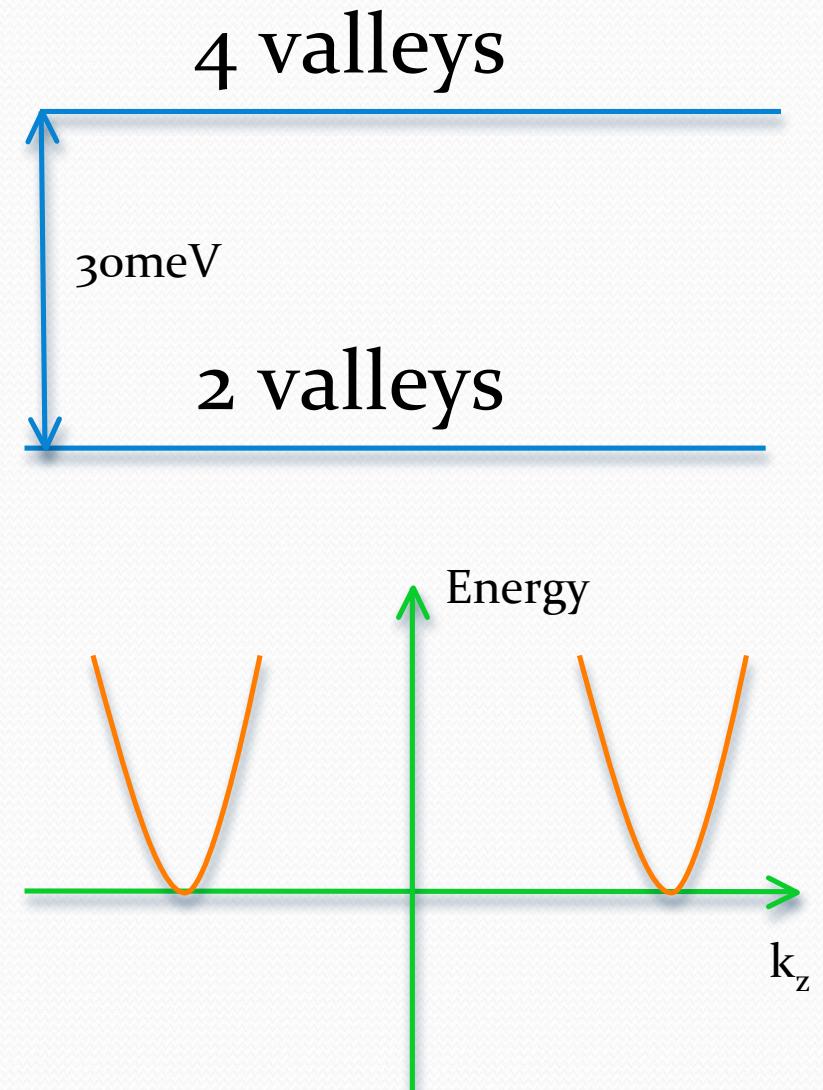
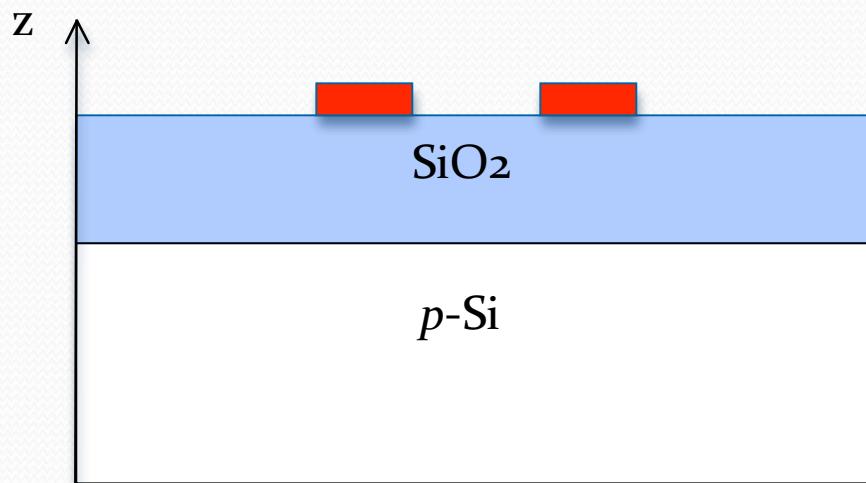
J. R. Petta et al, Science (2005)

Can we get better spin coherence times?



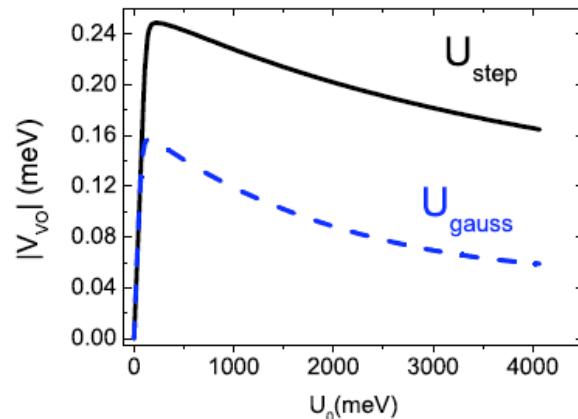
Valleys in Si 2DEG

- Confinement
 - 2 low-energy valleys
 - \perp interface
 - 4 higher-energy valleys
 - Split by $\sim 30\text{meV}$
- Only care about 2 valleys
 - $k_z = \pm 0.85 (2\pi/a)$

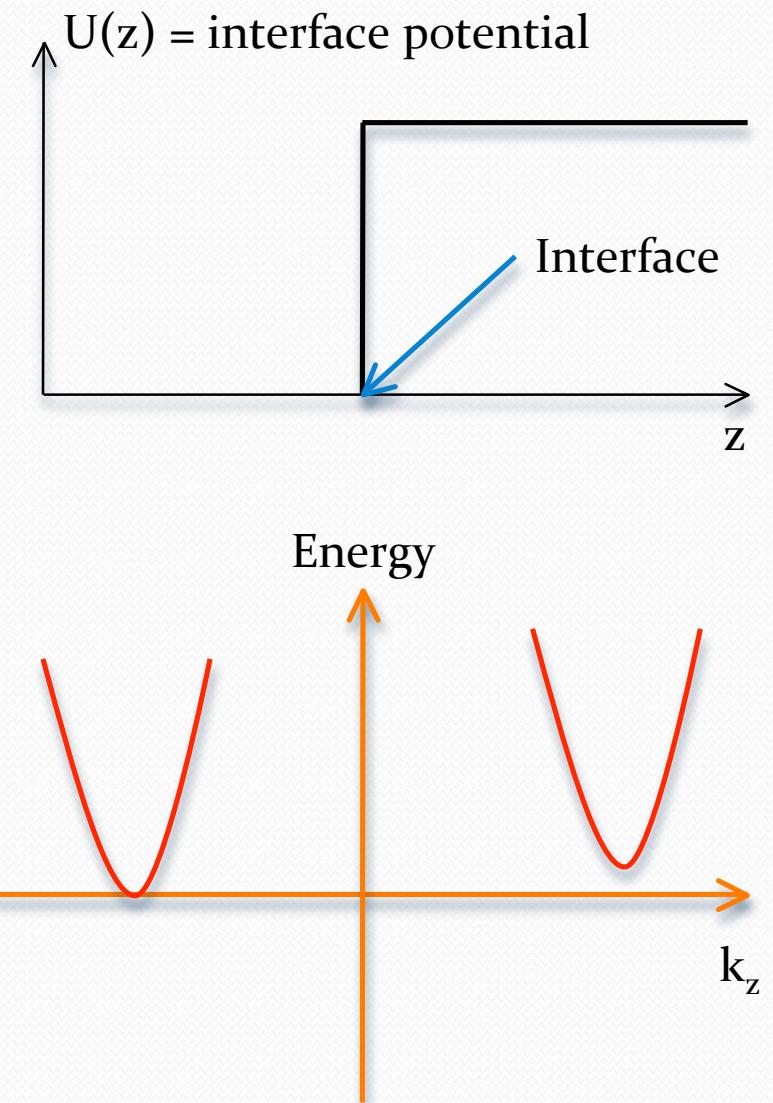
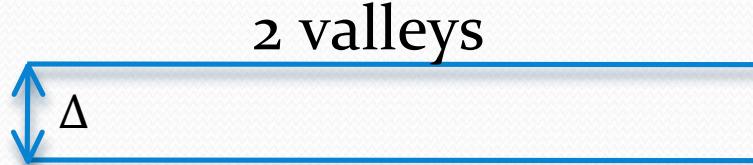


Valley-orbit coupling

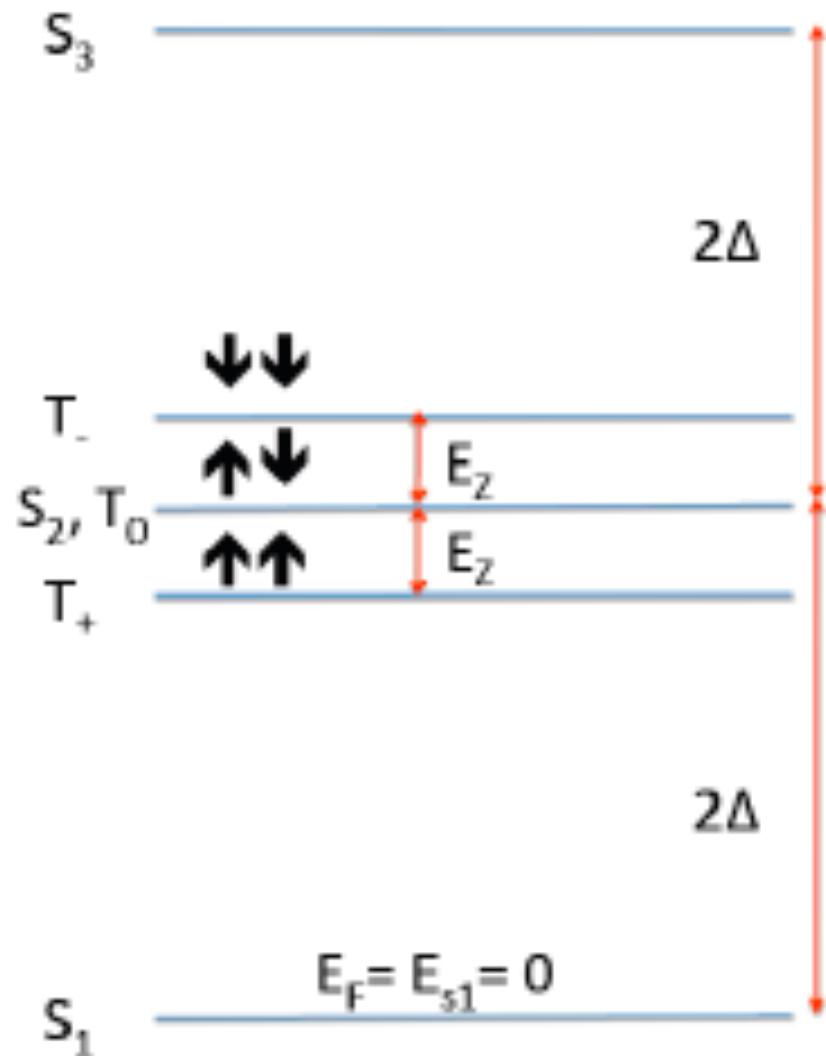
- In general valleys do not mix
- Need sharp potential
- Interface gives valley splitting
- Valley eigenstates $\pm\Delta$



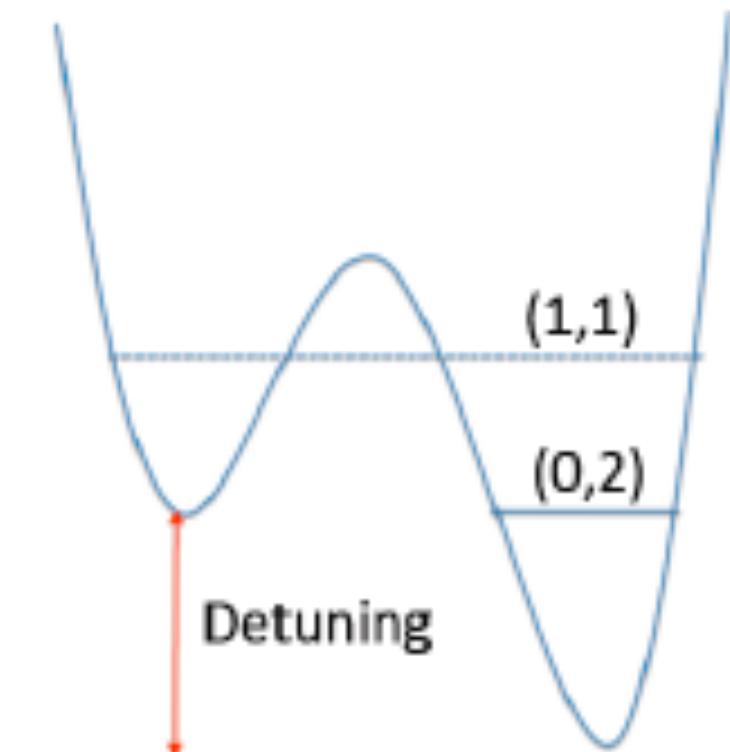
Saraiva et al, arXiv:0901.4702
Friesen and Coppersmith arXiv:0902.0777



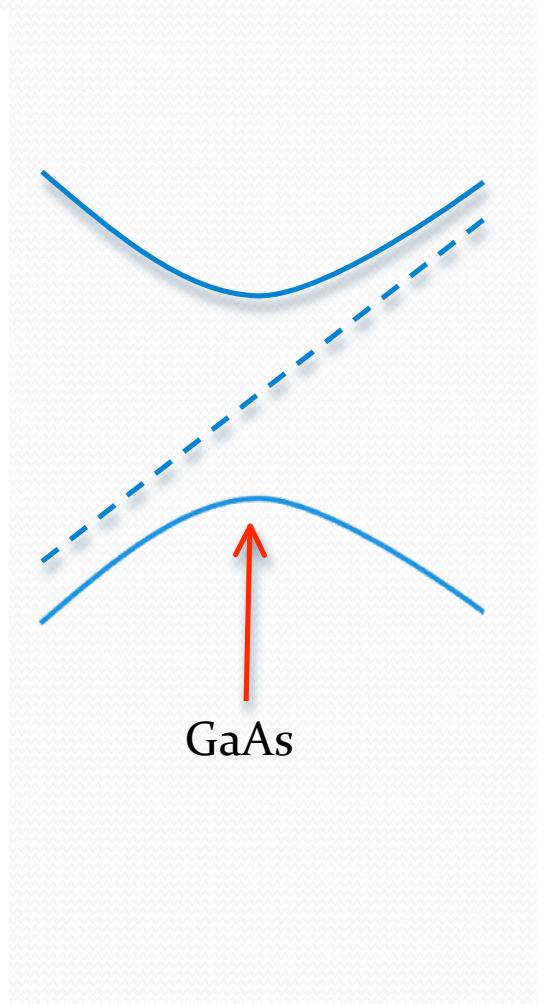
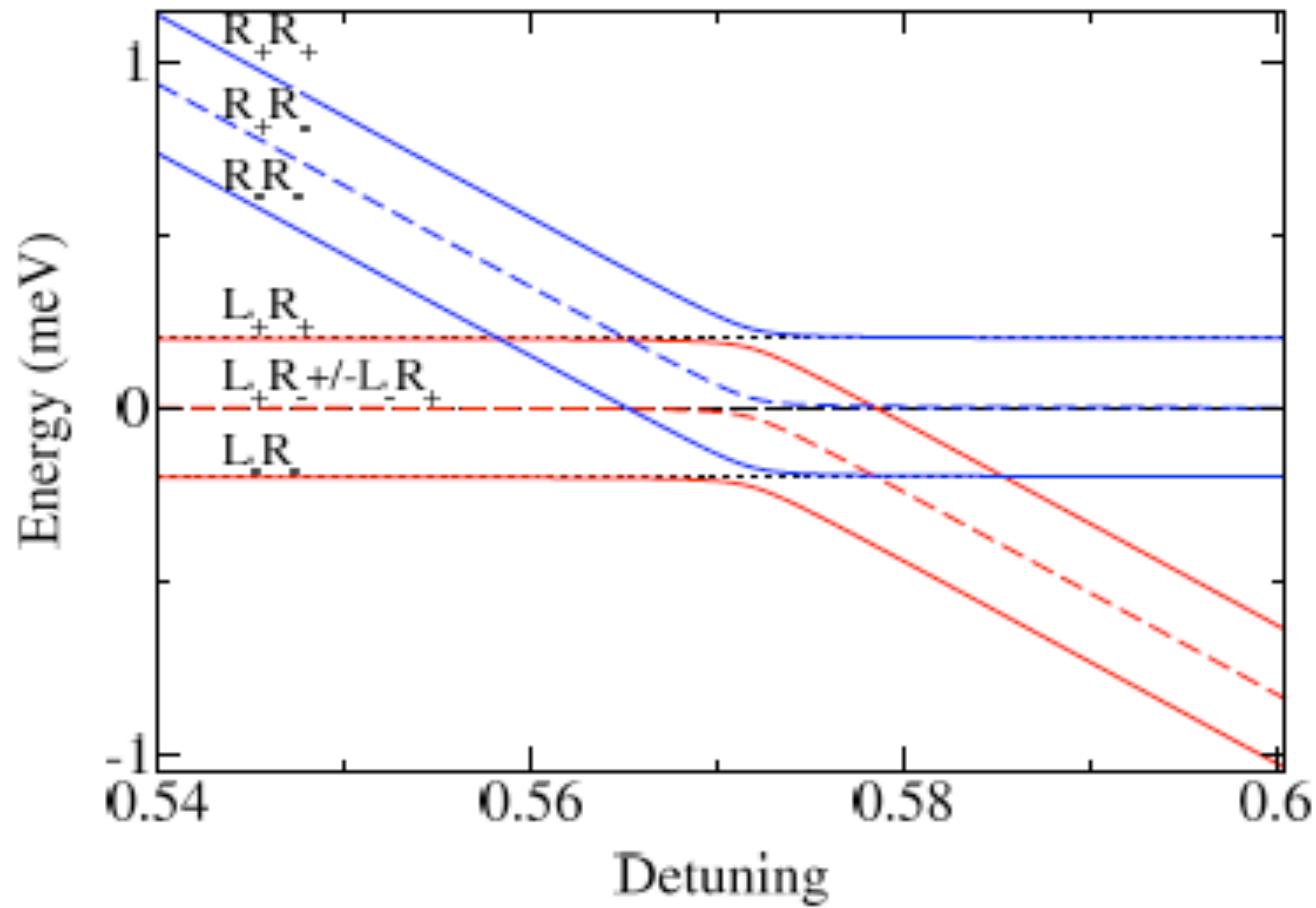
Si single dot



WE NEED LARGE Δ !

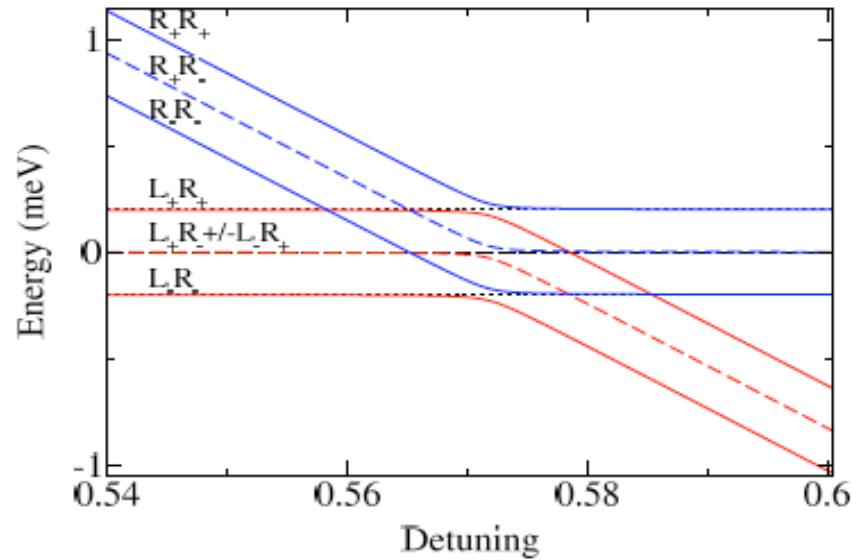
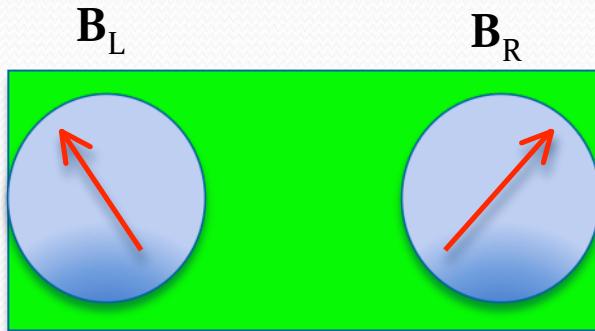


Si double dot

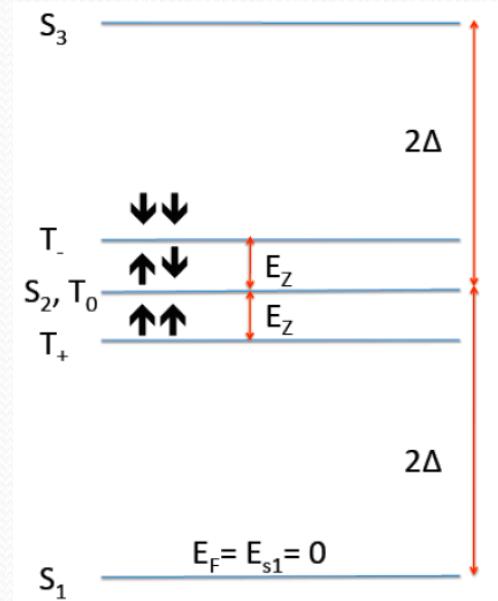
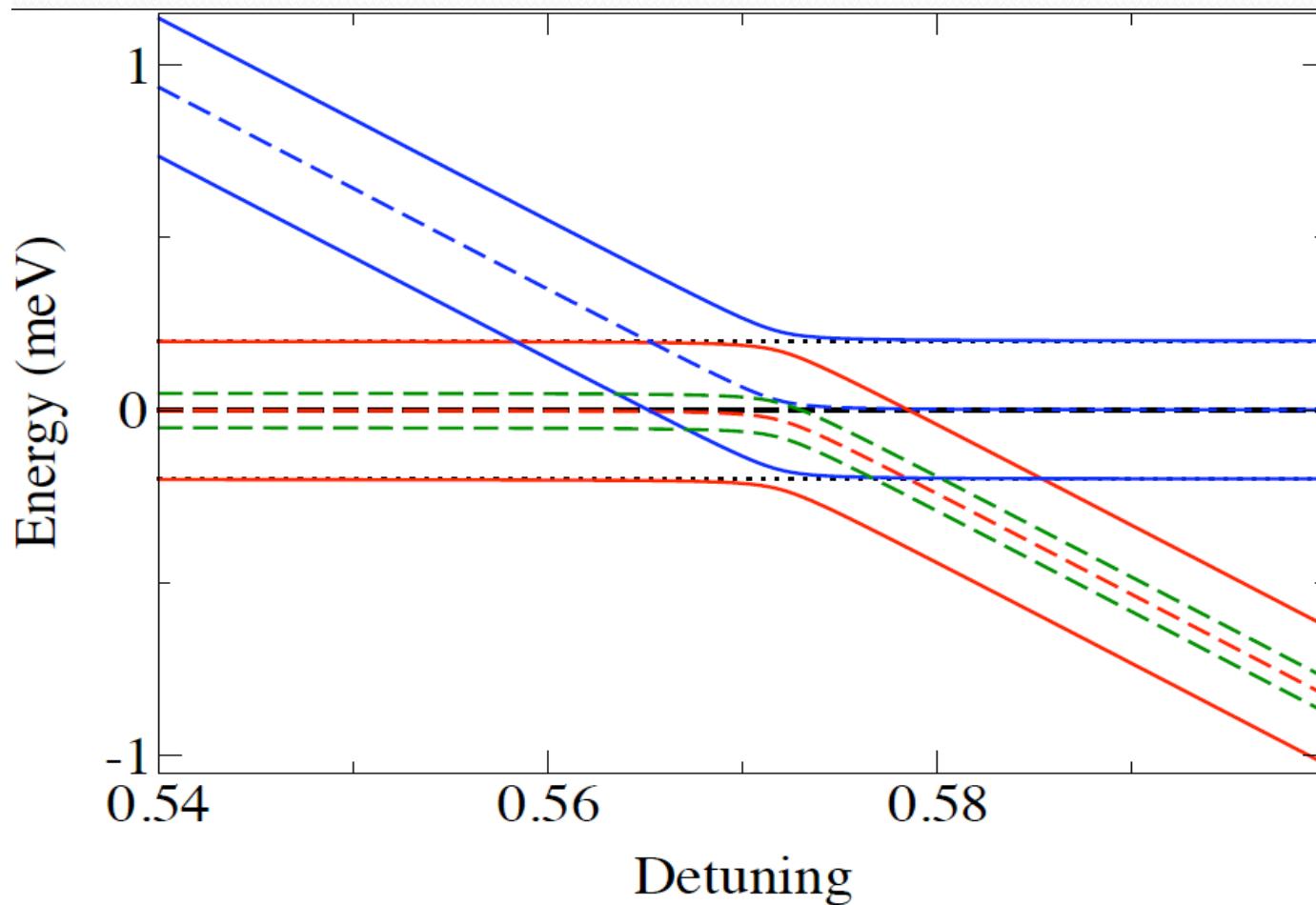


Mixing in magnetic field

- Hyperfine in Si is very small
- Put in a nanomagnet
 - Tailor magnetic field to mix what you want
- Valley eigenstates do not mix
 - Mixing in magnetic field same as in GaAs
 - Load S, mixes with T from same regime
 - Load T, mixes with S from same regime

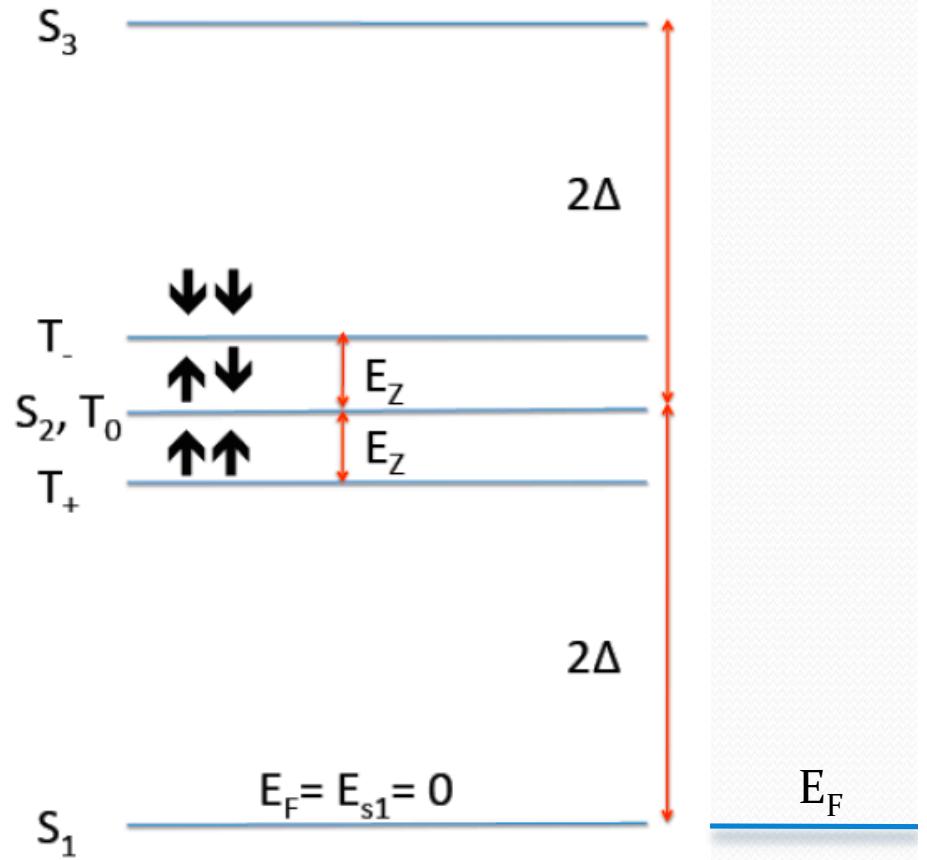


Singlet-triplet qubit in Si



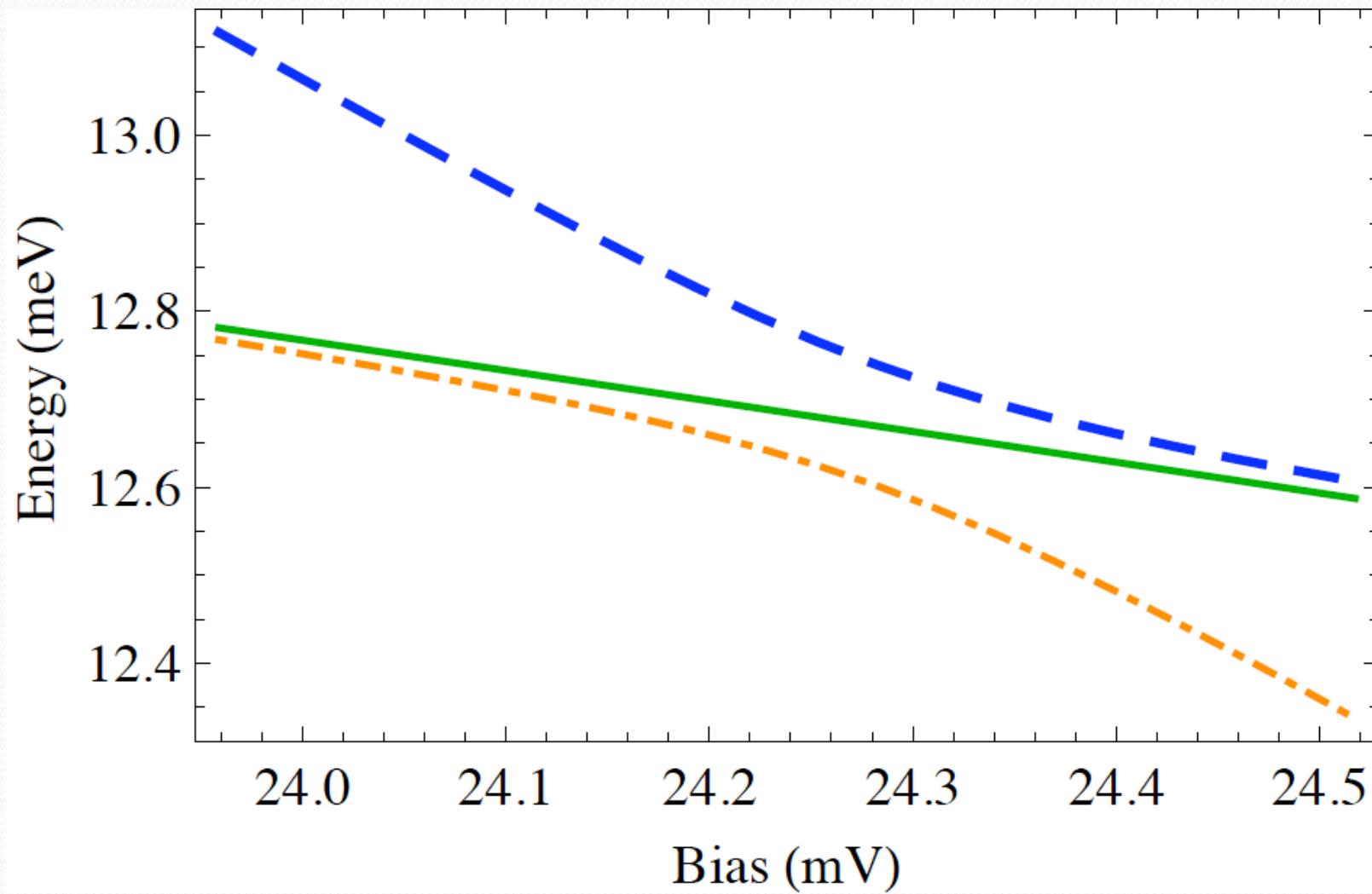
Measuring the valley coupling

- Loading probability \propto Fermi function
- Different levels have different probabilities of return
 - High field
 - Some are $1/2$
 - Some are 0 because they do not mix with anything
- Thus sweeping the magnetic field can tell us the valley coupling

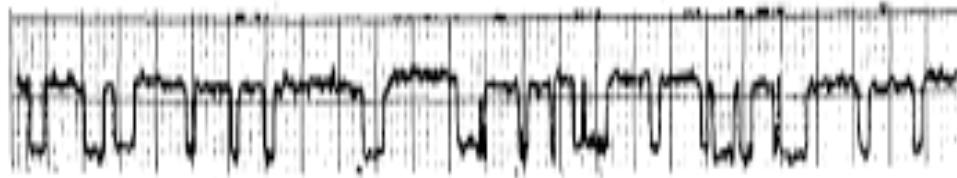
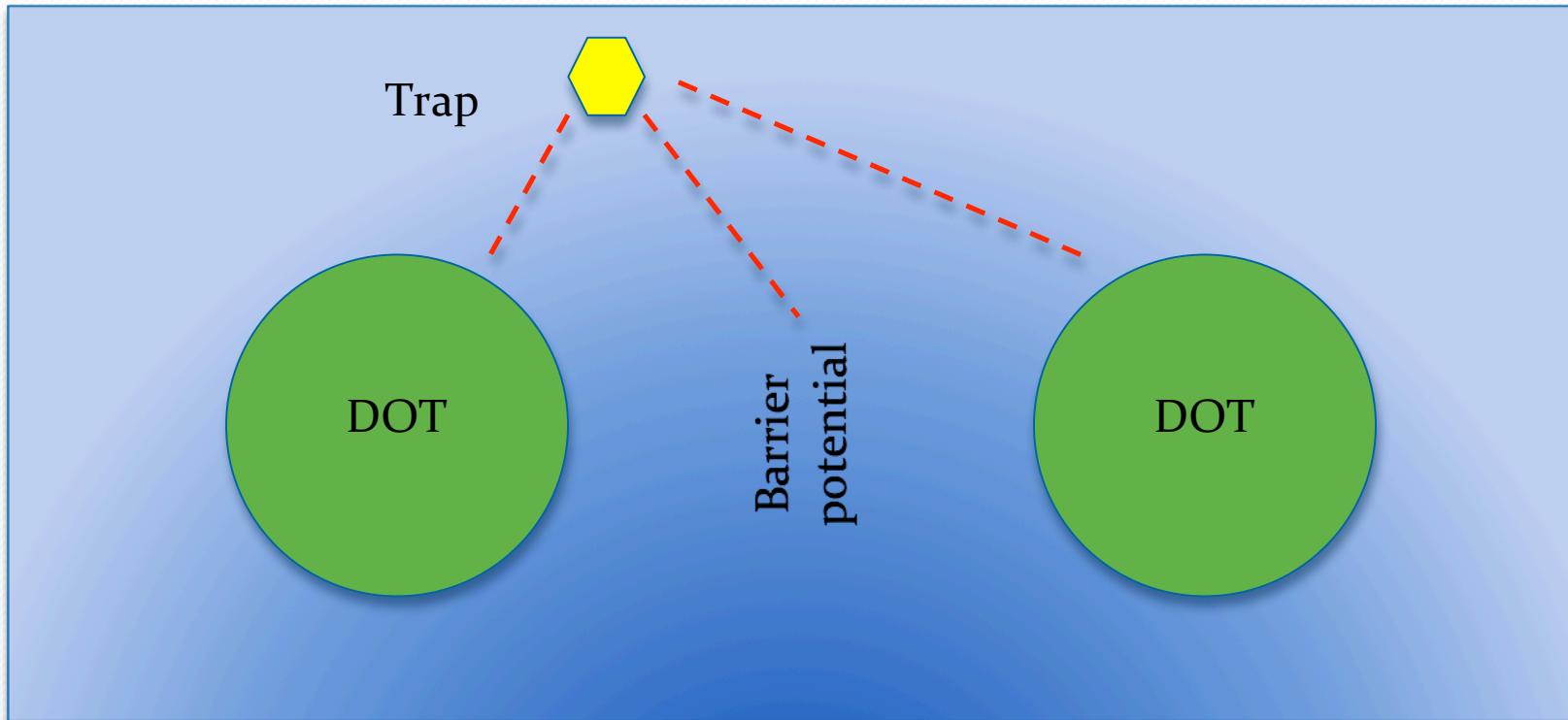


Ideal case: large valley splitting

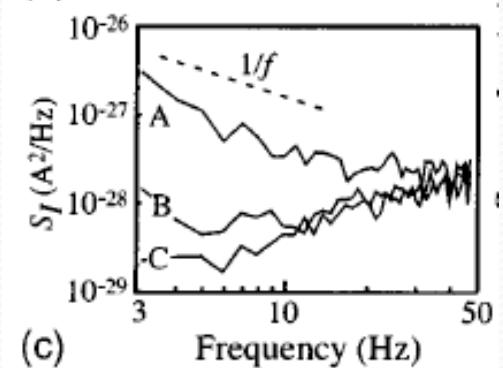
- Single-valley situation



Background charge fluctuations



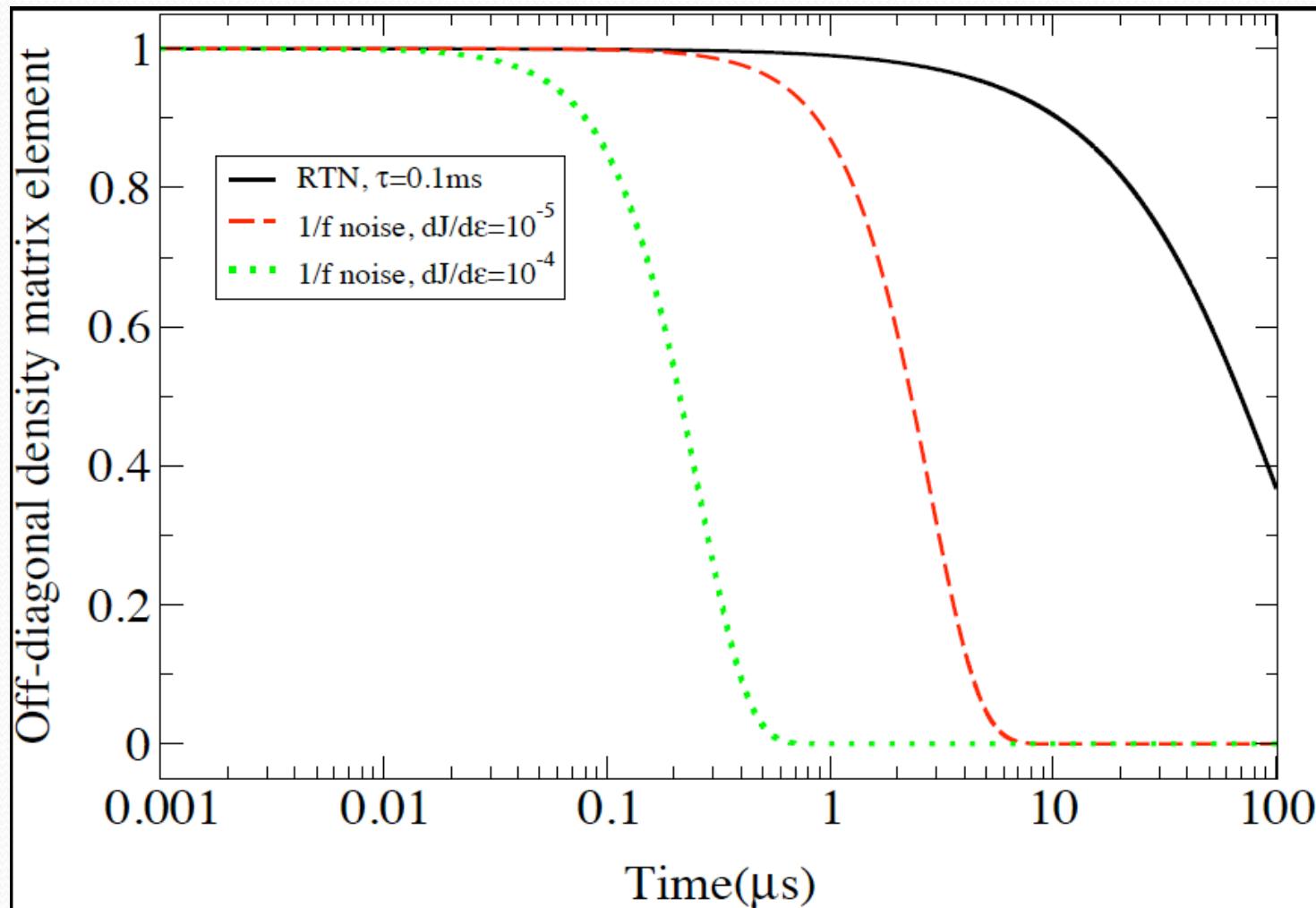
Ralls et al, PRL 52, 228 (1984) → MOSFET



Jung et al APL 85, 768 (2004) → GaAs QDs

Noise-induced dephasing

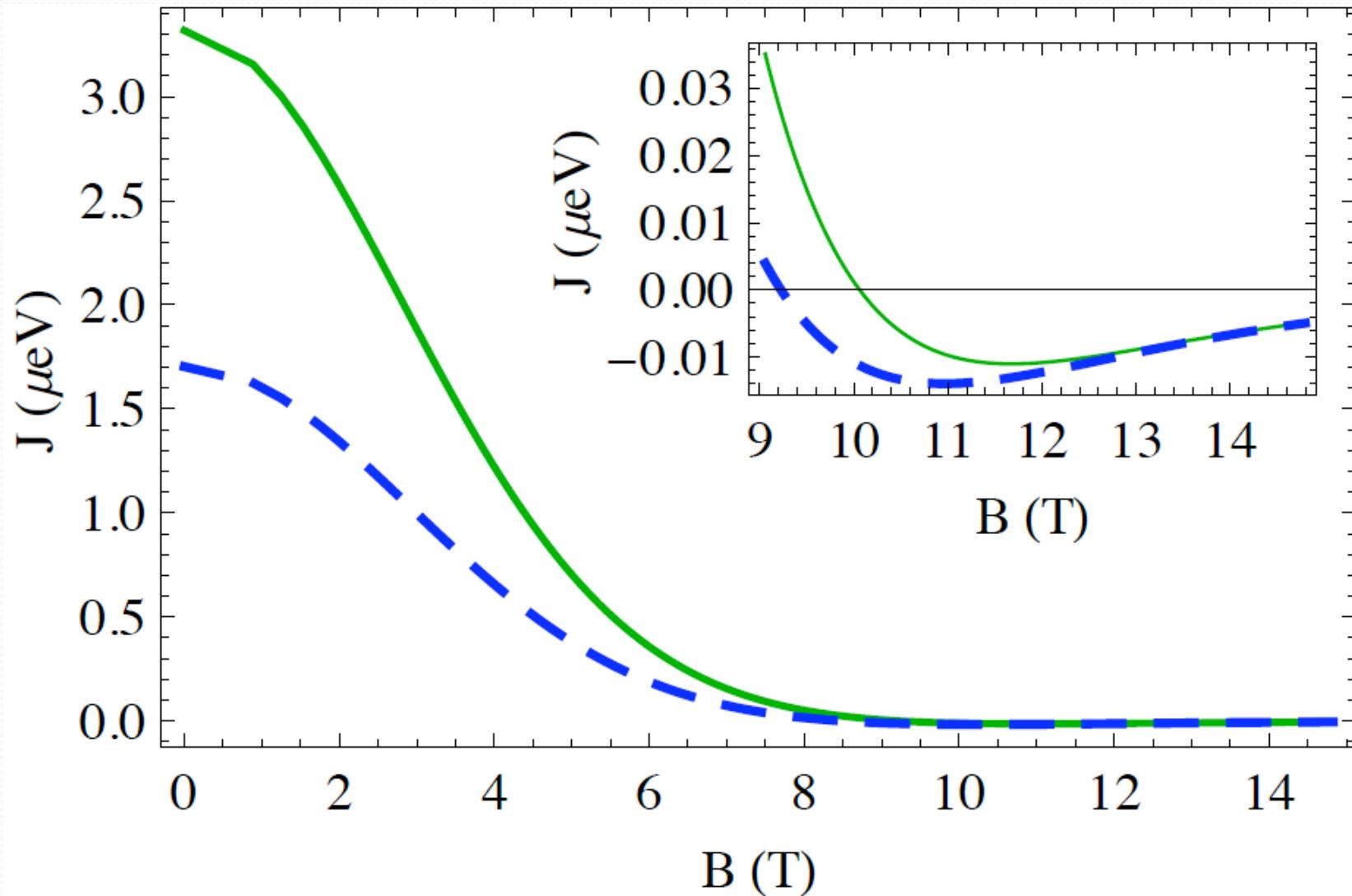
- Generate off-diagonal DM element $\rightarrow T_2$



See Xuedong Hu – next talk 1130

D. Culcer, X. Hu, and S. Das Sarma, arXiv: 0906.4555, to appear in APL

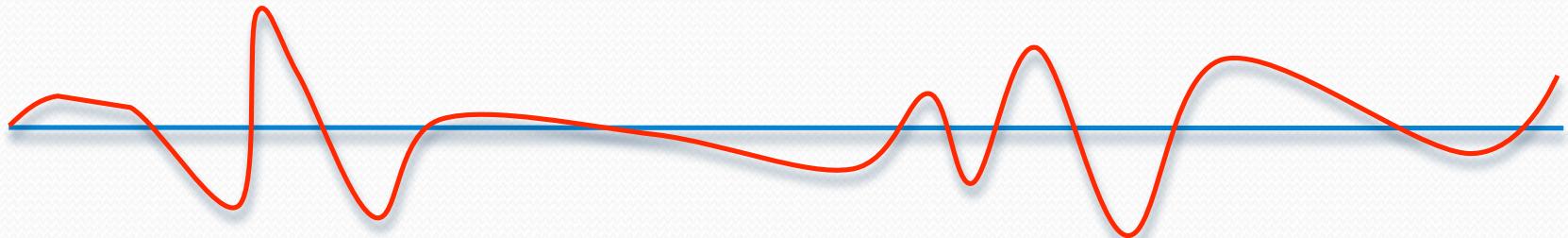
Sweet spot



Qiuzi Li, L. Cywinski, D. Culcer, X. Hu, and S. Das Sarma, arXiv: 0906.4793.
See also: M. Stopa and C. M. Marcus, Nano Letters **8**, 1778 (2008).

Interface roughness

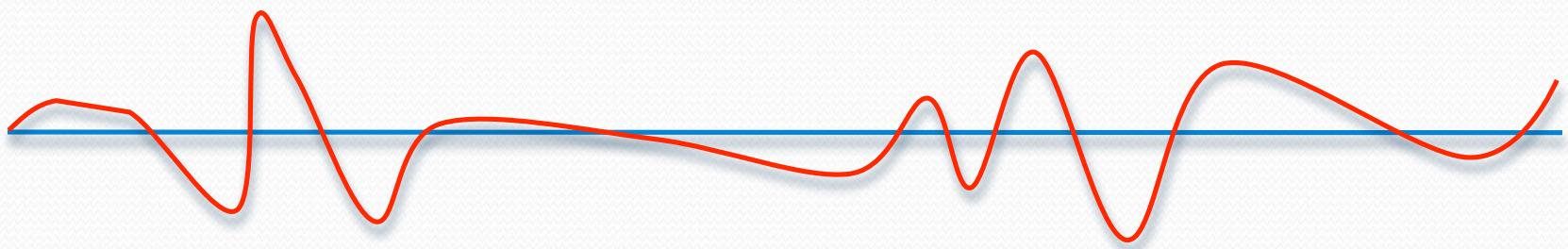
- We want a smooth interface
- But interface can be rough
 - Fast-varying term in interface potential
- Two dots
- Position-dependent valley coupling
- Valley eigenstates different in two dots
 - Possibly suppress tunneling
 - Difficult to manipulate qubit
- Dots must span area with little variation in roughness



D. Culcer, L. Cywinski, X. Hu, and S. Das Sarma, to be published.

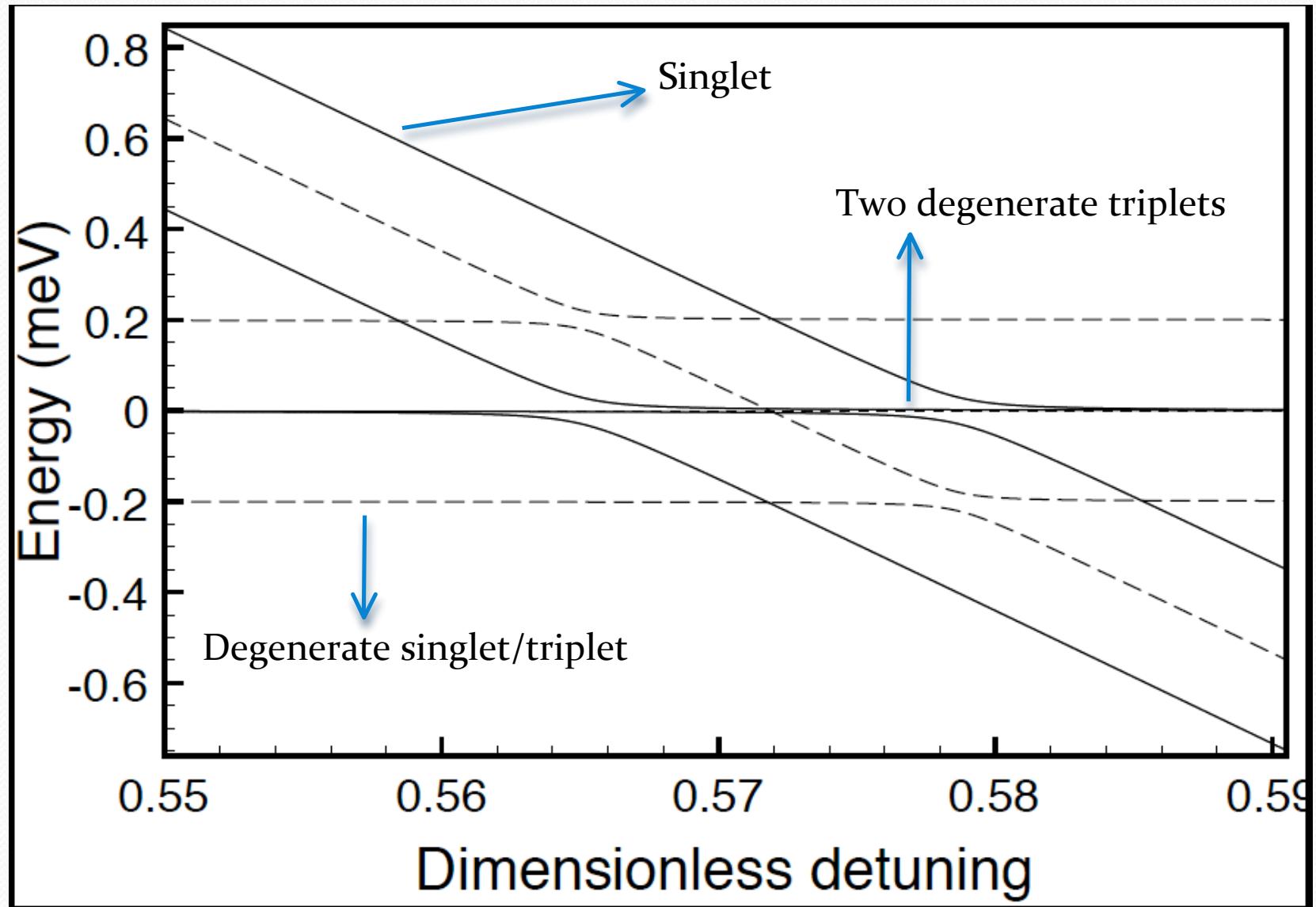
Interface roughness

- Valleys do not mix on same dot
 - Need very sharp perturbation in real space
- But they can mix during inter-dot transitions
 - Inter-dot inter-valley tunneling
- Variation in valley-orbit coupling
 - Variations in magnitude – can live with
 - The PHASE also varies: valley eigenstates vary
 - This causes inter-dot inter-valley tunneling
 - Can alter double-dot spectrum drastically



D. Culcer, L. Cywinski, X. Hu, and S. Das Sarma, to be published.

Extreme case: all tunneling inter-valley



D. Culcer, L. Cywinski, X. Hu, and S. Das Sarma, to be published.

Conclusions and Outlook

- Si QD spin qubits
 - Physics is highly non-trivial and interesting
 - Orbital freedom MUST be considered in quantum computing
 - Operational qubits if valley splitting $\gg k_B T$
 - Singlet-triplet qubit can be used to measure valley splitting
 - Probability of return in high magnetic field
 - RTN, 1/f qualitatively different dephasing
 - Need a ***smooth*** interface
- Outlook
 - Additional ways to measure valley splitting

D. Culcer, L. Cywinski, Q. Li, X. Hu, and S. Das Sarma, arXiv: 0903.08633.
Qiuzi Li, L. Cywinski, D. Culcer, X. Hu, and S. Das Sarma, arXiv: 0906.4793.
D. Culcer, X. Hu, and S. Das Sarma, arXiv:0906.4555, to appear in APL.
D. Culcer, L. Cywinski, X. Hu, and S. Das Sarma, to be published.